



**AFRL-AFOSR-VA-TR-2017-0013**

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Fundamental Studies of transient, atmospheric-pressure, small-scale plasmas

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**01/23/2017**  
**Final Report**

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14. ABSTRACT Fundamental studies of nanosecond pulsed atmospheric pressure plasmas including a millimeter He-O2 plasma jet, generated with a concentric tubular electrode configuration, and micrometer He plasma jet, generated with a single electrode, were conducted. These studies include 1) temporally and spatially resolved measurements of atomic oxygen ground state (O3P) in the 2-cm long, 1-mm He-O2 plasma jets using Two-Photon Absorption Laser Induced Fluorescence (TALIF); 2) plasma dynamics and emission spectroscopic comparisons of single-electrode helium microplasma jets that was excited with 5 ns or 164 ns, 8 kV pulses at 500 Hz. Applications of the atmospheric pressure plasma jets and jet arrays (e.g. plasma brush) were explored for surface decontamination against pathogenic bacteria and biofilms, as well as for treatment of cervical cancer, in vitro. Other studies involving portable nanosecond pulsed power generation based gas switches or photoconductive solid state switches, non-equilibrium surface plasma chemistry and applications were also conducted.					
15. SUBJECT TERMS					
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Subject: Final Report to Dr. Jason Marshall

Contract/Grant Title: Fundamental Studies of Transient, Atmospheric-Pressure, Small-Scale Plasmas

Contract/Grant #: FA9550-11-1-0190

Reporting Period: 15 Jul 2011 to 14 Jan 2017

#### Abstract:

Fundamental studies of nanosecond pulsed atmospheric pressure plasmas including a millimeter He-O<sub>2</sub> plasma jet, generated with a concentric tubular electrode configuration, and micrometer He plasma jet, generated with a single electrode, were conducted. **1)** Temporal development and spatial distribution of atomic oxygen ground state (O<sup>3</sup>P) in the 2-cm long, 1-mm He-O<sub>2</sub> plasma jets were measured using Two-Photon Absorption Laser Induced Fluorescence (TALIF) in collaboration with Dr. Campbell Carter at Wright-Patterson AFRL. Oxygen number density on the order of 10<sup>13</sup> cm<sup>-3</sup> in a 150-ns, 6-kV plasma jet was obtained for an axial distance up to 5 mm above the device nozzle. Electrostatic modeling and energy-dependent studies showed that the direct and indirect electron-induced processes in the pulsed plasma jet are responsible for the O production. **2)** A single-electrode helium microplasma jet was generated in ambient atmosphere when the electrode was excited with 5 ns or 164 ns, 8 kV pulses at 500 Hz. Spatially-resolved optical emission spectroscopy showed that the production of excited atomic oxygen increased by a factor of 2 for the 5 ns pulsed plasma jet when compared with that for a 164 ns pulsed plasma jet operating at the same voltage amplitude, pulse frequency, and flow conditions. This signifies an enhanced efficiency of atomic oxygen production by highly non-equilibrium plasmas excited with high voltage pulses with fast rising time and relatively short durations. Analysis of the rovibronic emission from N<sub>2</sub> (C-B) indicated a rotational and vibrational temperature of 300 K ± 50 K and 3000 ± 200 K, respectively, for both the 5 ns and 164 ns pulsed plasma jets. **3)** Applications of the atmospheric pressure plasma jets and jet arrays (e.g. plasma brush) were explored for surface decontamination against pathogenic bacteria and biofilms, as well as for treatment of cervical cancer, *in vitro*. **4)** Other studies involving portable nanosecond pulsed power generation based gas switches or photoconductive solid-state switches, non-equilibrium surface plasma chemistry and applications were also conducted.

#### Archival publications during reporting period:

- 1) C. Jiang, C. Schaudinn, D. E. Jaramillo, M. A. Gundersen, and J. W. Costerton, "A sub-microsecond pulsed plasma jet for endodontic biofilm disinfection," Z. Machala *et al.* eds. Plasma for Bio-Decontamination, Medicine and Food Security, NATO Science for Peace and Security Series A: Chemistry and Biology, DOI 10.1007/978-94-007-2852-3\_14, © Springer Science + Business Media B.V. 2012.
- 2) E. Sozer, M. A. Gundersen, and C. Jiang, "Magnesium Based Photocathodes for Back-Lighted Thyratrons," *IEEE Transaction on Plasma Science*, 2012, **40**(6): 1753-1758.
- 3) P. P. Sedghizadeh, M.T. Chen, C. Schaudinn, A. Gorur, and C. Jiang, "Inactivation Kinetics Study of an Atmospheric-Pressure Cold Plasma Jet against Pathogenic Microorganisms," *IEEE Transactions on Plasma Science*, 2012, **40**(11). DOI: 10.1109/TPS.2012.2213306.
- 4) C. Jiang and C. Carter, "Absolute atomic oxygen density measurements for nanosecond pulsed atmospheric pressure plasma jets using two-photon absorption laser-induced fluorescence spectroscopy," *Plasma Sources Science and Technology*, **23**(6): 065006, 2014. DOI: 10.1088/0963-0252/23/6/065006.
- 5) M. A. Malik, C. Jiang, S. K. Dhali, R. Heller, and K. H. Schoenbach. "Coupled sliding discharges: a scalable nonthermal plasma system utilizing positive and negative streamers on

opposite sides of a dielectric layer,” *Plasma Chemistry and Plasma Processing*, **34**:871–886, 2014.

- 6) V. R. Potturi, M. A. Malik, K. H. Schoenbach and C. Jiang, “Low cost, multi-kilohertz pulse generator for non-equilibrium plasma-based air purification,” the 2014 IEEE International Power Modulator and High Voltage Conference Record, Santa Fe, NM, June (2014).
- 7) C. Jiang, J. Lane, S. Song, S.J. Pendelton, Y. Wu, E. Sozer, A. Kuthi, and M.A. Gundersen, “Single-electrode He microplasma jets driven by nanosecond voltage pulses,” *Journal of Applied Physics*, 119 (9) 083301, 2016. DOI: <http://dx.doi.org/10.1063/1.4942624>.
- 8) M. A. Malik, C. Jiang, R. Heller, J. Lane, and K. H. Schoenbach, “Ozone-free nitric oxide production using an atmospheric pressure surface discharge – a way to minimize nitrogen dioxide co-production,” *Chemical Engineering Journal*, 283: 631-638, 2016. DOI: <http://dx.doi.org/10.1016/j.cej.2015.07.092>.
- 9) W. Ren and C. Jiang, “LED-triggered photoconductive semiconductor switches for nanosecond pulse generation,” *Proceeding of 2016 IEEE International Power Modulator and High Voltage Conference*, July 5-9, 2016.
- 10) H. A. Ryan, S. Song, J. Neuber, S. J. Beebe, and C. Jiang, “Effects of a non-thermal plasma needle device on HPV-16 positive cervical cancer cell viability *in vitro*,” *Proceeding of the 38<sup>th</sup> Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, August 16-20, 2016.
- 11) C. Jiang and S. Song, “Ignition and dynamics of nanosecond pulsed helium streamers over a water electrode,” *Japanese Journal of Applied Physics*, 2016, in review.
- 12) S. Song, J. Lane, and C. Jiang, “Comparison study of spatiotemporally resolved emissions of nanosecond pulsed microplasma jets,” *IEEE Transactions on Plasma Science*, 2016, in review.
- 13) J. U. Neuber, S. Song, M. A. Malik, and C. Jiang, “Nanosecond pulsed plasma brush for bacterial inactivation on laminate,” *IEEE Transactions on Radiation and Plasma Medical Science*, 2017, in submission.

Changes in research objectives, if any: None

Change in AFOSR program manager, if any:

Changed from Dr. John Luginsland to Dr. Jason Marshall

Extensions granted or milestones slipped, if any:

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Fundamental Studies of Transient, Atmospheric-Pressure, Small-Scale Plasmas

**Grant/Contract Number**

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-11-1-0190

**Principal Investigator Name**

The full name of the principal investigator on the grant or contract.

Andras Kuthi/Chunqi Jiang

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Jason Marshall

**Reporting Period Start Date**

07/15/2011

**Reporting Period End Date**

01/14/2017

**Abstract**

Fundamental studies of nanosecond pulsed atmospheric pressure plasmas including a millimeter He-O<sub>2</sub> plasma jet, generated with a concentric tubular electrode configuration, and micrometer He plasma jet, generated with a single electrode, were conducted. 1) Temporal development and spatial distribution of atomic oxygen ground state (O<sup>3</sup>P) in the 2-cm long, 1-mm He-O<sub>2</sub> plasma jets were measured using Two-Photon Absorption Laser Induced Fluorescence (TALIF) in collaboration with Dr. Campbell Carter at Wright-Patterson AFRL. Oxygen number density on the order of 10<sup>13</sup> cm<sup>-3</sup> in a 150-ns, 6-kV plasma jet was obtained for an axial distance up to 5 mm above the device nozzle. Electrostatic modeling and energy-dependent studies showed that the direct and indirect electron-induced processes in the pulsed plasma jet are responsible for the O production. 2) A single-electrode helium microplasma jet was generated in ambient atmosphere when the electrode was excited with 5 ns or 164 ns, 8 kV pulses at 500 Hz. Spatially-resolved optical emission spectroscopy showed that the production of excited atomic oxygen increased by a factor of 2 for the 5 ns pulsed plasma jet when compared with that for a 164 ns pulsed plasma jet operating at the same voltage amplitude, pulse frequency, and flow conditions. This signifies an enhanced efficiency of atomic oxygen production by highly non-equilibrium plasmas excited with high voltage pulses

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- 1) C. Jiang, C. Schaudinn, D. E. Jaramillo, M. A. Gundersen, and J. W. Costerton, "A sub-microsecond pulsed plasma jet for endodontic biofilm disinfection," Z. Machala et al. eds. Plasma for Bio-Decontamination, Medicine and Food Security, NATO Science for Peace and Security Series A: Chemistry and Biology, DOI 10.1007/978-94-007-2852-3\_14, © Springer Science + Business Media B.V. 2012.
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13) J. U. Neuber, S. Song, M. A. Malik, and C. Jiang, " Nanosecond pulsed plasma brush for bacterial inactivation on laminate," IEEE Transactions on Radiation and Plasma Medical Science, 2017, in submission.

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No

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None

**Change in AFOSR Program Officer, if any:**

Changed from Dr. John Luginsland to Dr. Jason Marshall

**Extensions granted or milestones slipped, if any:**

No cost extension was granted from July 14, 2016 to January 14, 2017.

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**LRIR Title**

**Reporting Period**

**Laboratory Task Manager**

**Program Officer**

**Research Objectives**

**Technical Summary**

**Funding Summary by Cost Category (by FY, \$K)**

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